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Degree of Hybridization Modeling of a Fuel Cell Hybrid Electric Sport Utility Vehicle

Paul Atwood, Stephen Gurski, and Douglas J. Nelson
Virginia Polytechnic Institute and State University, Blacksburg, VA

Keith B. Wipke
National Renewable Energy Laboratory, Golden, CO

ABSTRACT

An ADVISOR model of a large sport utility vehicle with a fuel cell / battery hybrid electric drivetrain is developed using validated component models. The vehicle mass, electric traction drive, and total net power available from fuel cells plus batteries are held fixed. Results are presented for a range of fuel cell size from zero (pure battery EV) up to a pure fuel cell vehicle (no battery storage). The fuel economy results show that some degree of hybridization is beneficial, and that there is a complex interaction between the drive cycle dynamics, component efficiencies, and the control strategy.

INTRODUCTION

The main benefit of hybridization in a vehicle with an internal combustion engine is load leveling to improve the overall efficiency of the engine operating region. A fuel cell *stack* generally has relatively high efficiency at light load, and a fuel cell *system* may also have good part load efficiency depending on the system parasitic loads (primarily air compressor power). This part load efficiency makes fuel cells attractive for light duty vehicle loads, and would seem to eliminate the need for hybridization. But the start-up of a fuel cell system, including bootstrapping a high-voltage air compressor drive, and cold-start transient response power limitations, may require hybridization. While neither of these important issues are specifically addressed in the current work, the energy efficiency may still be improved through addition of some energy storage. Other reasons for hybridization include the cost, weight and volume of fuel cells relative to batteries, and the capture of regenerative brake energy. Some of these issues have been considered for a 1500 kg sedan by Friedman (1999) and Friedman et al. (2000).

Sport utility vehicles have a relatively large potential for fuel economy improvements. This class of vehicle has some specific uses and drive cycles (such as towing) that may preclude the downsizing of the main energy converter to improve efficiency.

An ADVISOR simulation model based on validated component models is presented to investigate the potential of hybridization to improve fuel economy of a large sport utility vehicle. The objectives of this analysis are to understand the efficiency interactions of fuel cells and batteries, and determine if there is an optimal configuration.

VEHICLE DESCRIPTION

The large sport utility vehicle (SUV) chosen for this analysis is based on a 2000 four-wheel drive Chevrolet Suburban LT converted to a fuel cell hybrid electric vehicle (FCHEV). For the current modeling, the exterior geometry of the vehicle stays the same, and the conventional internal combustion engine drivetrain is replaced with a fuel cell/battery series hybrid electric drivetrain. The basic vehicle parameters for this class of vehicle are listed in Table 1 below.

Table 1 Large Fuel Cell Hybrid SUV Parameters

Drag Coefficient	0.45
Frontal Area, m^2	3.17
Rolling Resistance Coefficient	0.008
Mass, kg	2900

The total mass shown for the converted FCHEV is set 400 kg higher than the stock vehicle to approximate the increased weight of the fuel cell and battery components, and then held constant for the results given here. The fuel cell system on the vehicle is assumed to be supplied by a compressed hydrogen gas storage system. The present work does not consider the difficult packaging issues of fuel cell components,

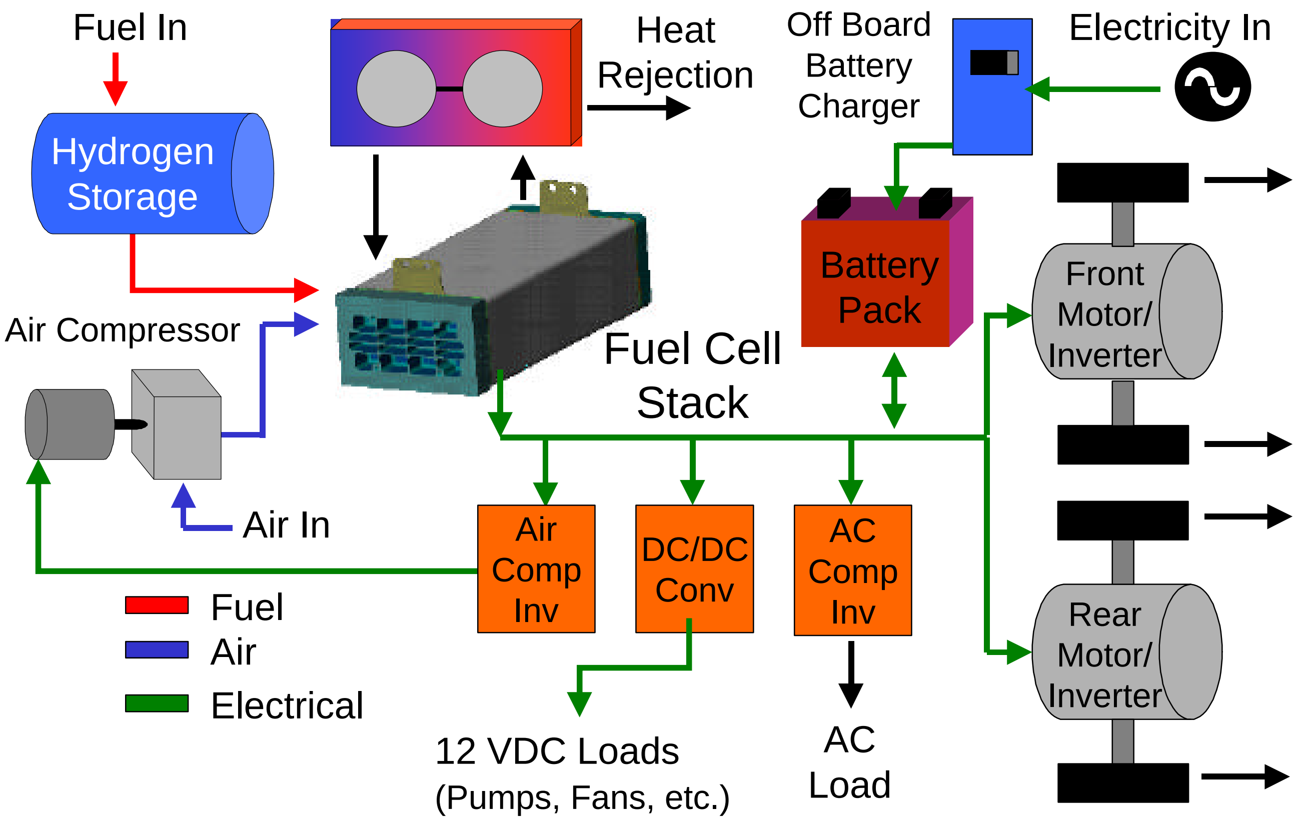

Figure 1. System Schematic of Fuel Cell Hybrid Electric Drivetrain Components

fuel storage, and range. Virginia Tech is currently developing a fuel cell hybrid Suburban for the FutureTruck competition sponsored by General Motors and the U.S. Dept. of Energy; See Patton et al. (2001) for more detailed information.

COMPONENT MODELS

ELETRIC DRIVETRAIN

A schematic of the components and energy flows for the overall vehicle model is shown in Fig. 1. The four-wheel electric traction drive consists of two, 83 kW AC induction motors to give the vehicle a total of 166 kW of tractive power. This power level is set to give the converted FCHEV acceleration, gradeability and towing performance similar to the stock vehicle (210 kW 5.3 l V8 engine). The motors have an integrated planetary gear reduction set that replaces the stock four-speed automatic transmission, and the vehicle is geared for a top seed of 130 kph (80 mph). The component model for the motor and inverter is based on a validated ADVISOR model (Senger et al., 1998).

FUEL CELL SYSTEM MODEL

The fuel cell system is based on measurements from a direct hydrogen 110 cell 20 kW gross system from Energy Partners (Fuchs et al., 2000). This system operates at a pressure of 1.7 atm at peak power using a twin screw compressor. An ADVISOR model of this system validated with measured hybrid fuel cell vehicle data is reported in Ogburn (2000) and Ogburn et al. (2000).

For this work, the fuel cell system is a constrained load following model with a minimum load, and the parasitic loads (air compressor drive and coolant pumps/fans) vary directly with fuel cell stack gross output power. The fuel cell model active area plus parasitic power are linearly scaled to generate the desired output power. The parasitic power represents about 24% of the gross stack power output at peak power. While this is not a particularly efficient system, it is based on measurements from currently available systems and components.

The fuel cell system model does not currently include any cold-start effects, either in the form of a fuel consumption or efficiency penalty, or in limited power output availability. Cold start issues are one of the reasons to hybridize a fuel cell vehicle.

BATTERY MODEL

The battery model is based on a 25 Amp-hour (Ah) Hawker Genesis sealed lead acid battery. The capacity and charge/discharge internal resistance maps are linearly scaled to generate battery components with the desired characteristics. The power available from the batteries is calculated from the instantaneous power available at an average 60% state of charge (SOC). In all cases, twenty-eight, 12 V modules are used to match the vehicle nominal bus voltage for the electric drivetrain.

VEHICLE ADVISOR MODEL

The road load parameters from Table 1, the fixed electric drivetrain, and variable size fuel cell and battery components are implemented in an ADVISOR model of the FCHEV. A range of vehicle configurations using fuel cell component sizes from zero (a pure battery electric vehicle) up to a pure fuel cell vehicle (zero battery) are selected to investigate the degree of hybridization with fixed vehicle mass and thus performance. The power requirement for each configuration is determined by the drivetrain power and additional accessory loads. For this class of vehicle, the dual motor drivetrain requires a supply of approximately 166 kW and accessory loads (power steering, power brakes, 12V loads) are set at 1.5 kW. Based on these power requirements, approximately 170 kW net from the combination of fuel cells and batteries is needed. The ability to supply 170kW of power to the high voltage electrical bus of the vehicle ensures that the performance is limited by the drivetrain, and not the hybrid power system.

Figure 2 shows some example time series results for the highway driving cycle (top time trace) for a sample hybrid case. ADVISOR has the option to iterate for a zero net change in battery SOC over the cycle to provide consistent, SOC-corrected fuel economy results (no battery net energy contribution). The control strategy starts the fuel cell system when the battery SOC reaches 40%. (Not shown is that the control strategy would shut the fuel cell system off at 80% battery SOC). The control strategy operates the fuel cell system at a minimum power level (15% of gross stack power) and is load following otherwise. For all of the hybrid results given below, zero net SOC change over a drive cycle and the same control strategy are used.

This simulation model is used to evaluate the fuel economy and component efficiencies for different combinations of fuel cell and battery size operating on four different drive cycles, as presented below.

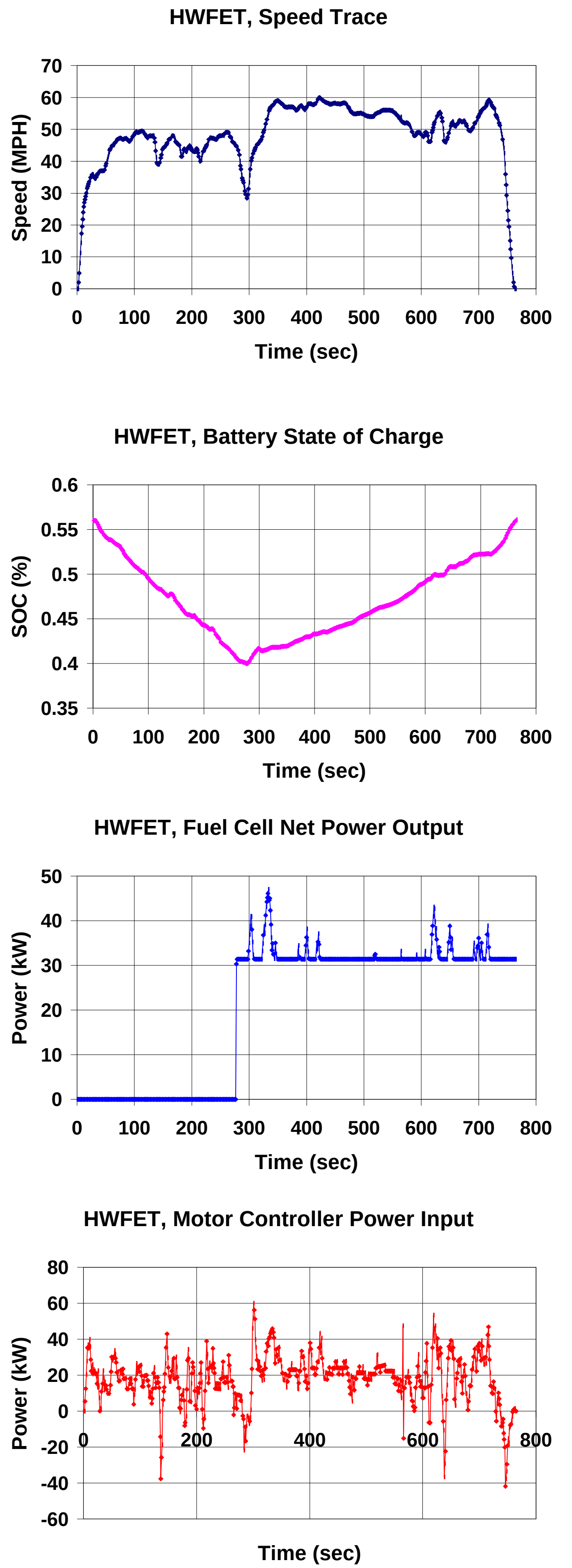

Figure 2. ADVISOR Model Results for a Highway Cycle

DEGREE OF HYBRIDIZATION RESULTS

For simplification purposes, the choices of fuel cell and battery size are set to uniform increments of 10 kW and 5 Ah, respectively. The lower limit of fuel cell power is chosen to ensure that the vehicle is at least charge sustaining at a constant speed of 103 kph (65 mph) on a level road. Thus, the minimum *net* power required from the fuel cell system is approximately 30 kW. This sets the lower bound of hybrid configurations at 40 kW *gross* stack power. The configurations of hybrid vehicles cover the spectrum from this lower limit up to the maximum net fuel cell power of 170 kW for the pure fuel cell vehicle configuration. The remaining power not supplied by the fuel cell determines the size of battery needed for a hybrid configuration.

The degree of hybridization is indicated by the ratio of gross fuel cell power in a hybrid configuration to gross fuel cell power for the pure fuel cell configuration (225 kW). This factor is also close to the ratio of net fuel cell power to net fuel cell plus battery power (= 170 kW). Table 2 lists the range of component sizes used to provide approximately constant available power.

Table 2. Hybrid Component Size Ratio

Ratio	Fuel Cell Gross kW	Fuel Cell Net kW	Battery Power kW	Battery Size Ah
0.00	0	0	170	80
0.18	40	30	140	60
0.22	50	38	135	55
0.27	60	45	120	50
0.31	70	52	120	50
0.36	80	61	110	45
0.40	90	68	95	40
0.44	100	75	95	40
0.49	110	84	85	35
0.53	120	91	70	30
0.58	130	99	70	30
0.62	140	106	60	25
0.67	150	114	60	25
0.71	160	122	50	20
0.76	170	129	50	20
0.80	180	137	35	15
0.84	190	145	25	10
0.89	200	152	13	5
0.93	210	160	13	5
1.00	225	171	0	0

The unadjusted, gasoline equivalent energy fuel economy (mpgge) results are presented in Figure 3. Four standard drive cycles of varying dynamics are investigated; the Urban Dynamometer Driving Schedule (UDDS or City cycle), the Highway Fuel Economy Test (HWFET or Highway cycle), part of the Supplemental FTP Test (US06 cycle), and a constant highway speed of 103 kph (65 mph) on a level road (C65). The two non-hybrid, limiting cases are described first.

PURE BATTERY ELECTRIC VEHICLE

The pure electric vehicle (EV) model is used as a reference limiting case. Since the primary assumption in selecting the battery size fixed total power, the range of this type of vehicle would probably not be practical using a lead-acid battery pack. The capacity of the battery pack is sized at 80 Ah to provide 170 kW of instantaneous power at 60% state of charge (SOC). The resulting range for this vehicle is about 50 miles at a constant speed of 103 KPH (65 MPH), or less than 40 miles on repeated US06 cycles (less than 5 cycles). The latter result probably gives a better indication of the real-world range for this battery-only electric vehicle.

The pure EV fuel economy results have a factor of 0.3 applied to account for power plant generation, plus wall-charger and battery charge efficiencies to convert energy use from the vehicle bus to miles per gallon of gasoline equivalent (mpgge) (Wang, 1999). The results from the ADVISOR simulations show fuel economy comparable to, but lower than the hybrid vehicles. The obvious disadvantage for this class vehicle is the limited EV range.

PURE FUEL CELL VEHICLE

The other limiting case is a pure fuel cell vehicle with no battery storage. In keeping with the assumption that all vehicles should have a fixed drivetrain and total available power, the pure fuel cell vehicle provides 171 kW net. This power is enough to provide the 166 kW drivetrain and 1.5 kW accessory loads. The same fuel cell model is used in each vehicle, including the non-hybrid pure fuel cell vehicle. For this model, a 225 kW gross power stack is selected, and the control strategy allows the system to operate at very low net power output. As shown in Fig. 3, this vehicle model produced lower fuel economy than any of the hybrid cases, except on the non-dynamic C65 drive cycle.

Since the vehicle has no energy storage capability, the regenerative energy available from deceleration cannot be captured. To see how much effect this has on fuel economy, a similar 225 kW model was run with a small 15 Ah capacity battery pack sized to capture most of the regenerative braking energy on the US06 cycle. This model produced fuel economy better than the pure fuel cell case (as expected), but not as good as some of the smaller hybrid cases for reasons discussed below.

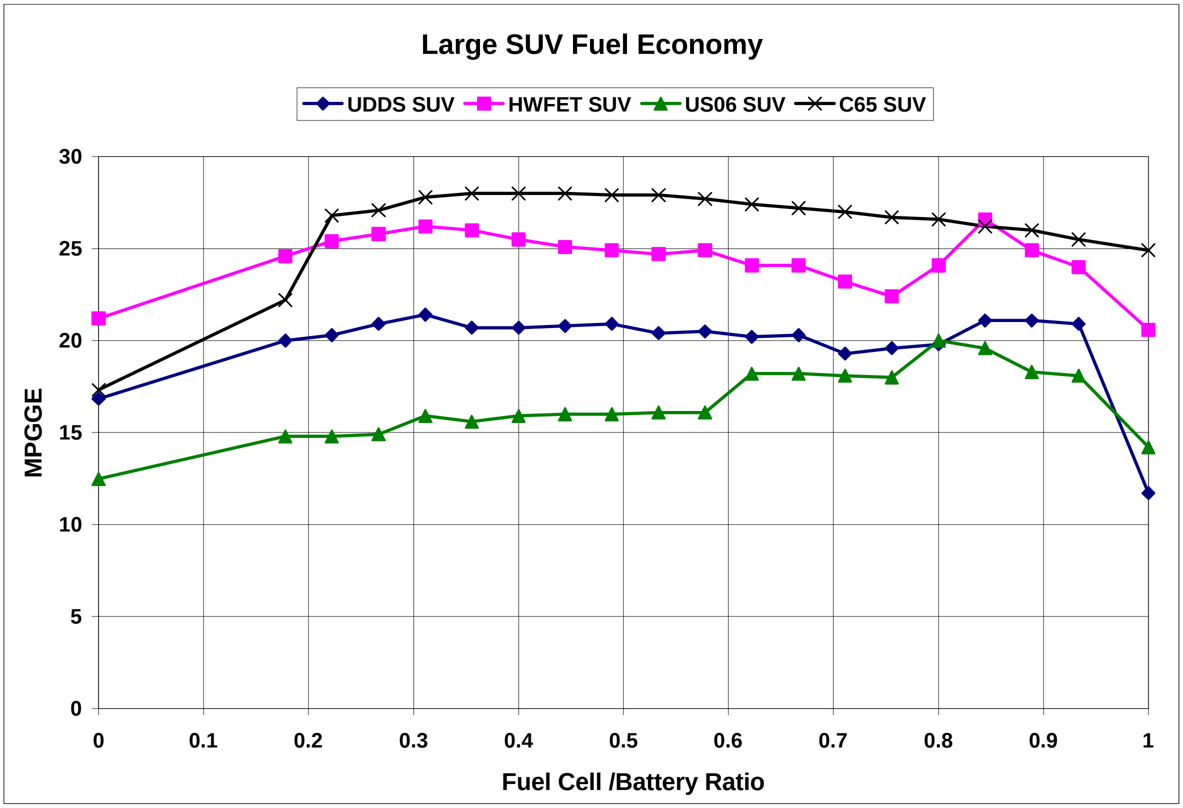

Figure 3. Fuel Economy Results for Degree of Hybridization

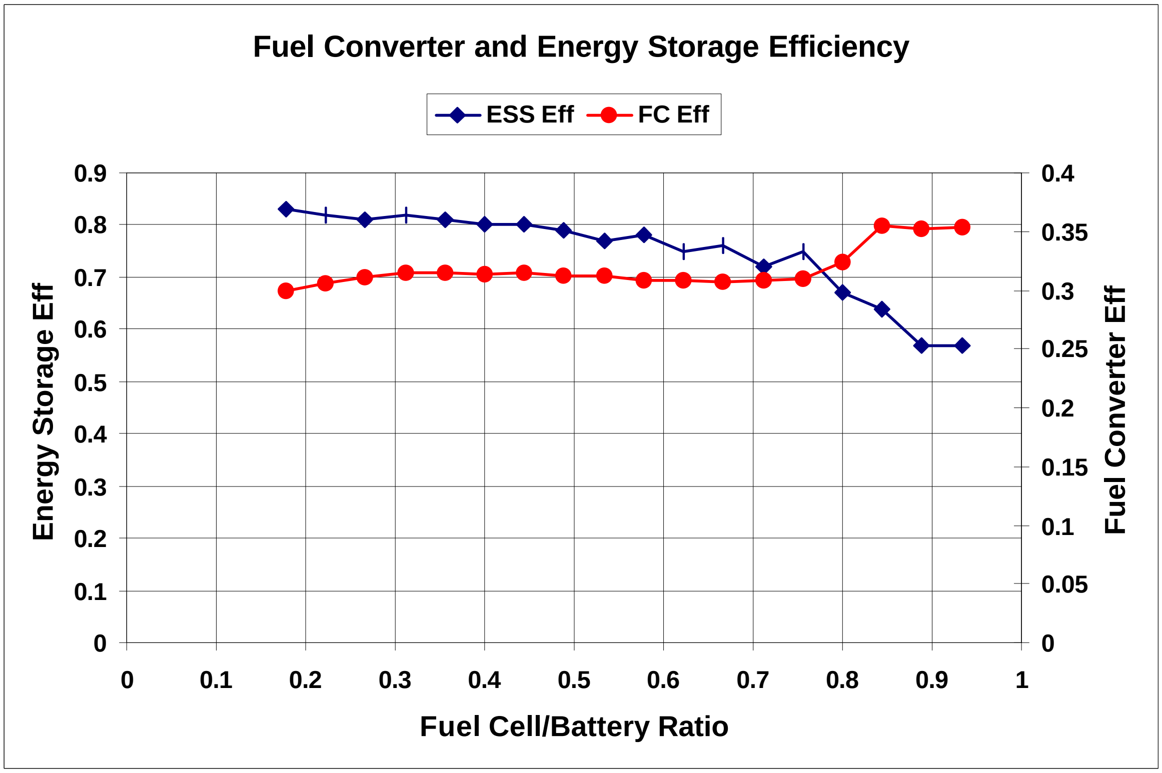

Figure 4. HWFET Component Efficiency Variation with Degree of Hybridization

HYBRID FUEL CELL/BATTERY VEHICLES

The choices for the hybrid fuel cell vehicle component configurations are governed by the fixed peak power requirement . Along with the fixed total mass and fixed drivetrain configuration, this method ensures that all hybrid configurations perform similarly. Consistent performance across all hybrid configurations ensures that variations in fuel economy are simply a result of fuel cell and battery size combinations, or degree of hybridization.

Hybrid Fuel Economy Results

The degree of hybridization fuel economy results shown in Fig. 3 depend on the dynamics of the drive cycle. For the constant highway speed cycle (C65), the initial increase is due to the increase in stack size and efficiency, then the fuel economy is relatively constant. The constant power required is always above the fuel cell minimum power criteria, so the control strategy does not play a role. There is no regenerative brake energy, so the battery size does not affect the results.

The more dynamic drive cycles all show a more complex interaction with degree of hybridization. The fuel economy rises somewhat with fuel cell size, then remains relatively constant or decreases before rising and dropping off again. The initial rise is from the increase in fuel cell size and efficiency as for the C65 case. As the fuel cell size continues to increase and the battery capacity decreases, the interaction between the power spectrum of the drive cycle, the minimum fuel cell power and the energy processed through the battery produces the peaks in fuel economy around degrees of hybridization of 0.8 - 0.9.

To help illustrate these interactions, Fig. 4 shows the HWFET cycle overall efficiency of the battery and fuel cell systems as the degree of hybridization varies. The peak in Highway fuel economy occurs where the fuel cell efficiency is highest. Figure 5 shows a sample of the Highway fuel cell power spectrum (kW-hr expended at a particular power level) along with the fuel cell net system part-load efficiency. For this size fuel cell, a large majority of the energy conversion occurs at the minimum fuel cell power level enforced by the control strategy. The choice of this minimum power level is evident in this figure – the fuel cell system efficiency drops off rapidly below this power. However, when the system is forced on and off to maintain this minimum power level, more energy must be processed through the round-trip charge/discharge penalty of the battery system. The fuel cell system model does currently use any penalty for start-up.

As the degree of hybridization increases, not only does the minimum power level increase with stack size, but the increased total energy processed through the smaller and small battery capacity leads to lower cycle average battery efficiency. Some of the decrease in fuel economy for high degrees of hybridization is also due to reduced ability to capture regenerative brake energy as the battery capacity shrinks.

For the fixed fuel cell and battery technology considered here (by scaling), the fuel cell size can have a 20% impact on fuel economy. The results do not show a single degree of hybridization that is best for all drive cycles. The control strategy and minimum power may have a significant impact on these results. Other considerations may also dictate a minimum fuel cell size, such as towing performance.

TOWING PERFORMANCE

The goals of reducing or eliminating vehicle emissions while increasing energy efficiency of vehicles should not sacrifice any of the vehicle performance capabilities. One aspect of sport utility vehicle design is towing characteristics. Analyzing a vehicle while towing a heavy trailer offers a look at sustained high power driving cycles. The towing cycles presented here consist of constant speeds of 88, 80, and 72 kmh (55, 50, and 45 mph) on a constant grade of 5%. The vehicle simulation starts at the cycle speed, so there is no acceleration at the beginning of the cycle. For these cases, the vehicle is equipped with a 3000 kg (6600 lb) trailer, to give a gross combined vehicle weight of 5900 kg (13,000 lb). This weight is similar to the gross combined towing weight rating of some drivetrain configurations of a production Suburban. Because the vehicle is a hybrid, and constant mass, power and performance are assumed, some hybrid configurations are charge-depleting (battery SOC is reduced) with a finite driving range. The towing performance is evaluated by how far the vehicle is able to travel before it can no longer sustain the cycle speed (due to reduced battery power at low SOC). Each case is started with an initial battery SOC of 80%.

The results in Fig. 6 yield two areas of interest. The first area lies at low fuel cell gross power, and low vehicle range. As the gross fuel cell power increases from 40 kW, the range decreases somewhat. The rate at which the fuel cell power output increases does not make up for the decrease in energy storage of the batteries until the gross fuel cell power is around 70 kW.

The second area of interest in Fig 6. is the last point in each of the three data sets. There is a finite amount of power required by the towing cycle at each speed. Once the fuel cell system net power can meet this power level, the vehicle is charge sustaining at that speed and the range is limited by fuel rather than battery power and SOC. These results suggest that a degree of hybridization greater than 60% (130 kW gross stack power) should provide good towing performance.

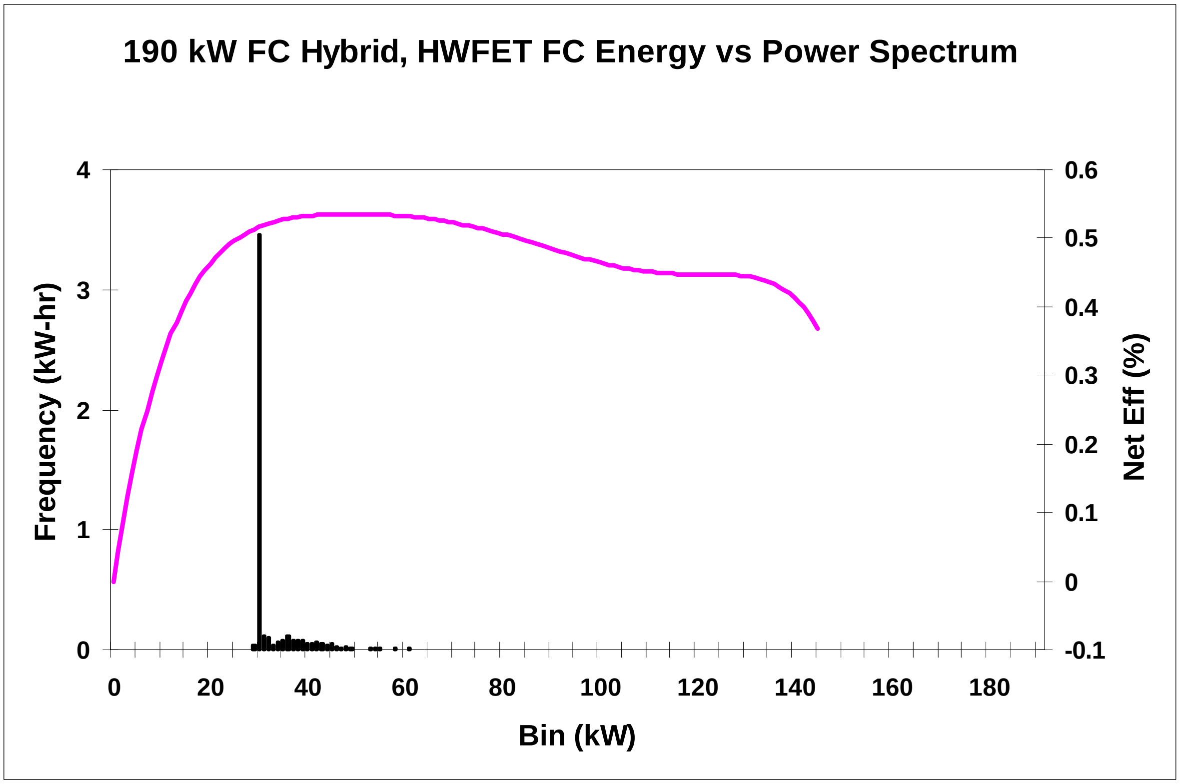

Figure 5. Fuel Cell Power Spectrum and Part-Load Net System Efficiency

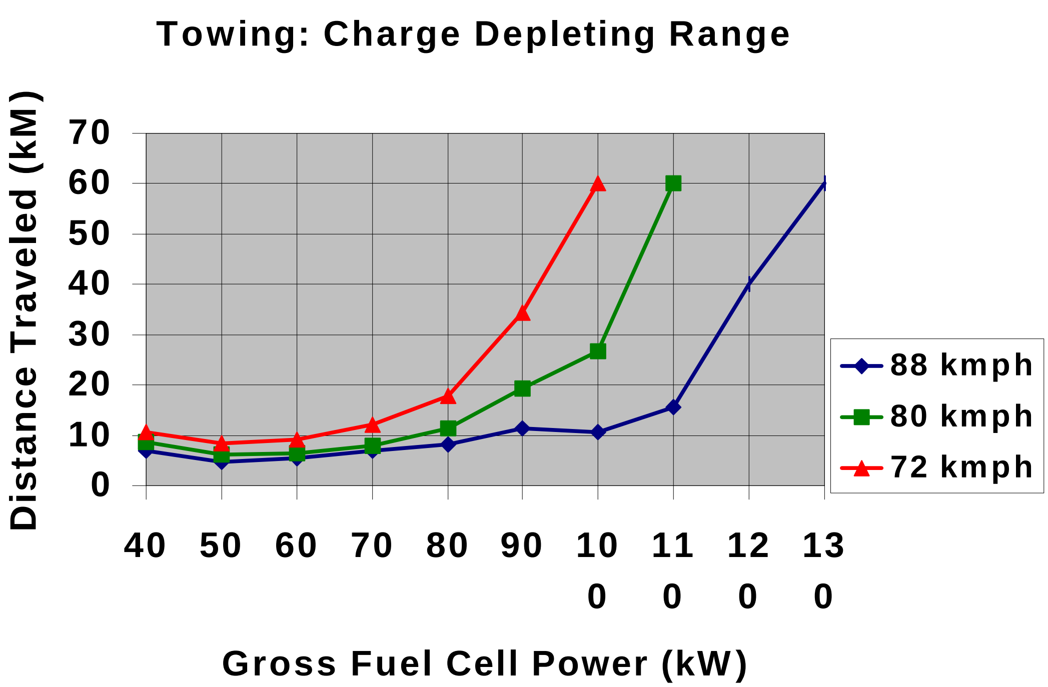

Figure 6. Towing Results

CONCLUSION

The results presented isolate the effect of fuel cell size on vehicle fuel economy for a wide range of degree of hybridization. The constraints imposed on the current results are:

- Fixed total vehicle mass
- Fixed electric traction drive
- Fixed total net power from fuel cell and battery
- Fixed vehicle performance (as a result of above)
- Fixed component technology, scaled in size/power
- Compressed hydrogen fuel
- No cold-start effects considered.

The fuel economy results demonstrate that some degree of hybridization can improve energy efficiency. As expected , some battery storage allows for capture of regenerative brake energy (and this energy is significant for this vehicle mass). The results also show that the control strategy for minimum fuel cell power, the power spectrum of the drive cycle, and of course the fuel cell and battery efficiency interact in a somewhat complex way. For the fuel cell system technology considered here, the low-load system efficiency depends on the air compressor power and minimum air compressor speed, and the control strategy for minimum fuel cell power, combined with battery size relative to the energy storage demand. For this class of large SUV, depending on the factors above, the fuel cell system may benefit from downsizing somewhat to prevent excessive operation at light load or on/off operation due to minimum power requirements. A clear optimum fuel cell size does not appear that is independent of the drive cycles considered. Towing requirements may dictate a minimum fuel cell power to maintain charge sustaining operation on a long grade.

Future work will consider cold-start effects, fuel cell and battery technology and efficiency, and control strategy impact.

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CONTACT

Dr. Douglas J. Nelson
GATE Center for Automotive Fuel Cell Systems
Virginia Polytechnic Institute and State University
Mechanical Engineering Department
Blacksburg, Virginia 24061-0238
(540) 231-4324 Doug.Nelson@vt.edu